



A dynamic viticultural zoning to explore the resilience of terroir concept under climate change

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HIGHLIGHTS

- Climate change has effects on terroir concept resilience.
- Dynamic viticultural zoning is able to explore the resilience of terroir concept.
- Few soil-plant and atmosphere systems are able to cope future climate condition.
- The future climate scenarios have shown a strong effect on viticultural sector.

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ABSTRACT

Climate change (CC) directly influences agricultural sectors, presenting the need to identify both adaptation and mitigation actions that can make local farming communities and crop production more resilient. In this context, the viticultural sector is one of those most challenged by CC due to the need to combine grape quality, grapevine cultivar adaptation and therefore farmers' future incomes. Thus, understanding how suitability for viticulture is changing under CC is of primary interest in the development of adaptation strategies in traditional wine-growing regions. Considering that climate is an essential part of the terroir system, the expected variability in climate change could have a marked influence on terroir resilience with important effects on local farming communities in viticultural regions.

From this perspective, the aim of this paper is to define a new dynamic viticultural zoning procedure that is able to integrate the effects of CC on grape quality responses and evaluate terroir resilience, providing a support tool for stakeholders involved in viticultural planning (winegrowers, winegrower consortiums, policy makers etc.). To achieve these aims, a Hybrid Land Evaluation System, combining qualitative (standard Land Evaluation) and quantitative (simulation model) approaches, was applied within a traditional region devoted to high quality wine production in Southern Italy (Valle Telesina, BN), for a specific grapevine cultivar (Aglanico). The work employed high resolution climate projections that were derived under two different IPCC scenarios, namely RCP 4.5 and RCP 8.5. The results obtained indicate that: (i) only 2% of the suitable area of Valle Telesina expresses the concept of terroir resilience orientated towards Aglianico ultra quality grape production; (ii) within 2010–2040, it is expected that 41% of the area suitable for Aglianico cultivation will need irrigation to achieve quality grape production; (iii) by 2100, climate change benefits for the cultivation of Aglianico will decrease, as well as the suitable areas.

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1. Introduction

Climate change (CC) directly influences agricultural sectors in ways that depend both on the magnitude and type of climatic change, in

terms of spatial patterns of climate variables (e.g. precipitation and temperature) and on local capacity to absorb these changes (Li et al., 2011).

Together with the growing world population and phenomena of soil degradation, these CC effects raise the food security issue for which the United Nations has identified Sustainable Development Goal n°2, “End hunger, achieve food security and improved nutrition and promote sustainable agriculture”.

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At the same time, several other key objectives of agricultural research have emerged. These include making local farming communities and crop production more resilient to CC, dealing with scarcity of natural resources, developing mitigation and adapting solutions to natural hazards.

Achieving these objectives also has important repercussions for farmers' incomes, which of course depend not only upon crop yields, but also on the quality of production, and thus the knowledge of specific pedo-climatic conditions can help to identify the best mitigation solutions for farmers and agricultural districts affected by climate change.

Among high income crops, the grapevine is considered one of the most challenged by climate change (Goode, 2012; Jones and Webb, 2010).

Evaluation of the future effects of CC has to be made in different ways for different crops, for example food crops (e.g. maize) have to be evaluated according to their responses in terms of adaptability and yield (Monaco et al., 2014; Sommer et al., 2013), while expected quality must be taken into account for grapevine (Bonfante et al., 2017). Moreover, it is important to stress that understanding how and how much land suitability for viticulture is changing as a result of CC is of primary interest in i) allowing the development of adaptation strategies in traditional wine-growing regions, ii) exploring cultivation potential in other regions (e.g. previously cooler ones) where climate change is creating more favourable thermal conditions (Jones, 2012).

In the Mediterranean area of southern Europe, a decrease in rainfall associated with an increase in temperature is expected (IPCC, 2014), leading to a marked effect on soil water availability.

As it is clearly expressed in the literature, these conditions will produce a reduction in food crop yields according to the concept of Water Productivity (Steduto et al., 2009), and, thus, in farmer's incomes. On the other hand, water scarcity has a direct effect on grape quality because it is strongly related to the degree of water stress experienced by plants during the growing season (Acevedo-Opazo et al., 2010; Bonfante et al., 2015b; Bonfante et al., 2017; Intrigliolo and Castel, 2011; Van Leeuwen, 2009). This well-established effect of plant water status is not surprising considering that water is the main regulator of the hormonal balance of grapevines (Champagnol, 1997).

Moreover, the change in average temperature will affect growing season length and, therefore, the cultivar adaptation to specific regions or sites (Gladstones, 1992). Mullins et al. (1992) reported that the growing season necessary for the cultivation of wine grapes varies from region to region, but it should, on average, be 170–190 days approximately. In contrast to average temperature, extreme temperature events can have negative effects on crop growth, yield and quality (Jones et al., 2012). In particular, during the vegetative growth, temperatures below -2.5°C can adversely affect the growth of vegetative parts of the plant and hard freezes can reduce yield significantly, while extreme heat (temperature $>35^{\circ}\text{C}$), in either the growing or ripening season, can have a negative impact on wine grape production (inhibition of photosynthesis, (Gladstones, 1992), colour development and anthocyanin production (Mori et al., 2005).

In literature, the effect of CC on grapevines are usually assessed in terms of phenological and physiological behaviour and expressed by different types of bioclimatic indices. According to (Jones et al., 2012) many different indices can be used such as those based (i) on temperatures, (ii) on solar radiation and temperature, (iii) on precipitation or also (iv) on plant water status. In further detail, some authors (Barnuud et al., 2014; Lorenzo et al., 2013; Moriondo et al., 2013; Santos et al., 2013; Van Leeuwen et al., 2013; Neethling et al., 2012) used indices related to the temperature and/or solar radiation (Growing Degree Days - GDD, Amerine & Winkler, Huglin Index, Biologically Effective Degree-Days index) while others have used combined indexes based on rainfall (e.g. Fraga et al., 2012, 2014, hydrothermal index - Hyl or Dryness Index), or as in the case of Brillante et al. (2016) and Leibar et al. (2015) physiological indices related to plant water status (Leaf Water Potential, Solar Noon Stem Water Potential) or biomass

production (Bindi et al., 1996). In one case, the effect of CC on grapevines has been evaluated in terms of grape quality by means of an integrated analysis of the Soil-Plant-Atmosphere (SPA) system through a process-based simulation model (Bonfante et al., 2017). This last analysis was based on the Crop Water Stress Index (CWSI) which expresses effects of water shortages on plant response in terms of grape quality.

The term CWSI is common in literature, it was used by different authors as Sudar et al. (1981), Jackson et al. (1981) and Jones (1999), and calculated in several ways (e.g. based on evapotranspiration, vegetation temperatures, conservation of energy for a cropped surface etc.). Then, different variables (e.g. air temperature, wet-bulb temperature, etc.) could be applied to develop a proper water stress index, but the use of transpiration information is a more realistic variable to define the crop water stress (Kozak et al., 2006). In this work the CWSI is calculated on the base of vine vegetation transpiration (ratio between actual and potential transpiration) as reported in Bonfante et al. (2017).

To summarise, the effects of CC in a specific region have a marked impact on grapevine cultivar adaptation, leading to high uncertainty about expected grape quality.

Considering the above, it is very important to incorporate CC in viticulture planning and managing procedures. In the viticultural sector, the planning and managing of high quality wine vineyards is typically carried out by means of viticultural zoning procedures (Carey, 2001; Gladstones and Smart, 1997; Vaudour, 2003). These are an extension - at a finer scale - of the standard concept of terroir, defined as "a spatial and temporal entity with homogeneous or outstanding grape and/or wine, soil landscape and climate characteristics, at a given spatial level or over a given duration, within a territory marked by social context and cultural technical choices" (Vaudour, 2003).

The viticultural zoning method is not unique, sometimes it is limited by its empirical approach in which the quantitative link between the climate-soil-plant system and wine is empirically or statistically described (e.g. Brousset et al., 2010), but not analysed with regard to its mechanics (Bonfante et al., 2015b; Bonfante et al., 2011). Regardless of the method, currently viticultural zoning does not include the evaluation of the effects of CC on grapevine adaptation and berry and wine quality, for which a quantitative dynamic approach is indeed required.

Thus, future planning requires a reliable assessment of the expected effects of climate change on both crop yield and quality through an integrated analysis of the components of different agricultural systems (e.g. soil, climate, plant), as can be performed properly by dynamic simulation modelling approaches (quantitative approaches) integrated with a quantitative approach (Land Evaluation, FAO, 1976; Manna et al., 2009) within a Hybrid Land Evaluation system (HLES), as proposed by Bonfante et al. (2015a) for maize.

More specifically, on the basis of the terroir concept and the role spatial interaction within the soil-plant-atmosphere system (SPA) has in grapes and wine quality, it is correct to think that expected climate change variability could concretely affect the resilience of terroirs within a viticultural district, with important consequences for local farming communities. Therefore, in this context, a new dynamic viticultural zoning procedure which can take into account the effects of CC on the SPA system, and, thus, on grape quality, is needed. This procedure should be able to provide a support tool for stakeholders involved in viticultural planning (winegrowers, winegrower consortiums, policy makers etc.) by identifying for which zones and for how long the concept of terroir can be considered resilient for a specific vineyard and target area.

From this perspective, the aim of this paper is to define a dynamic viticultural zoning procedure to evaluate grape quality responses and terroir resilience under CC.

To achieve these aims, a Hybrid Land Evaluation System (HLES), combining qualitative (standard Land Evaluation system) and quantitative (simulation modelling application) approaches, was applied to a traditional region devoted to high quality wine production in Southern Italy (Valle Telesina, BN) for a specific grapevine cultivar (Aglianico). This was done by taking into consideration high resolution climate

projections derived through the regional model COSMO-CLM on the basis of two different IPCC emission scenarios, namely RCP¹ 4.5 and 8.5.

2. Materials and methods

2.1. Methodology applied

The methodology applied was a Hybrid Land Evaluation system (HLES), similar to that reported in Bonfante et al. (2015), which consisted of three principal steps in which qualitative and quantitative approaches to land evaluation were used, in a key-out system, in order to perform dynamic viticultural zoning that was able to explore the terroir resilience concept.

The applied methodology storyline is (Fig. 1):

STEP 1: compare the thermal requirements of a given grapevine cv with the thermal conditions to be expected following the future climate-change scenarios within a target region. If the requirements are not met, the evaluation exercise can be terminated;

STEP 2: if the thermal requirements are met, the soil being considered is screened in terms of its suitability for plant growth, using an empirical Land Evaluation procedure, based on environmental characteristics (e.g. slope, aspect...etc.) and soil qualities and characteristics of Soil Typological Units (STUs). If some areas the Land Use Requirements (LUR_s) for a specific crop are satisfied, they are classified as suitable, the procedure is continued. If not, it is terminated.

STEP 3: the soil-plant-atmosphere system (SPA) model will be applied to the area considered as suitable in STEP 2 in order to evaluate the Crop Water Stress Index (CWSI), as a function of the climatic and soil moisture regime, and to classify the suitability (five suitable classes: S1, S2, S3, S4, S5) of functional Homogeneous Zones (fHZs)² to the production of grapes of differing levels of quality.

In the applied procedure crop nutrition stress and its effects on grape quality was not taken into account.

The aptitude of identified fHZs, and then the suitability to the production of grapes of differing levels of quality was defined through the frequency analysis of quality grape results determined by following the procedure published by Bonfante et al. (2017), in which the CWSI_{cum-h} values obtained from application of the simulation model were related to four levels of grape quality.

At the end of the procedure, an analysis of the potential resilience of the terroir concept for a specific grapevine cv. within a target region should be performed.

2.2. Study area

The work was performed in the “Valle Telesina” site in southern Italy (Fig. 2). This area, of about 20,000 ha, is a very complex landscape with a high soil spatial variability.

Valle Telesina has a composite geomorphology and an elongated east–west graben where the Calore River lies. Five different landscape systems are present (Fig. 2): (i) limestone mountains, with volcanic ash deposits at the surface; (ii) hills, comprised of marl arenaceous flysch; (iii) a pediment plain, comprised of colluvium material from the slope fan of the limestone reliefs; (iv) ancient alluvial terraces; and (v) the actual alluvial plain.

Such complexity is echoed in the 60 STUs, the main soil types include Silandic, Melanic, Mollic, Eutrosilic, Vitric Andosols, Haplic and Vertic Calcisols, Vertic Leptic Cambisol, Haplic Regosol, Vitric Phaeozem, Vitric Luvisol, Calcic Kastanozem, Vitric Kastanozem, Fluvic Cambisol. Soil Types are spatially aggregated into 47 soil mapping units (Terribile

et al., 2015). The study area is traditionally suited to the production of high-quality wine and olive oil (Bonfante et al., 2011; Terribile et al., 2017) in the hilly areas, while beech and chestnut forests are present in the mountain system, where there is a natural park.

For further information about the study area see (Bonfante et al., 2011; Terribile et al., 2017).

2.3. Crop and thermal requirements

The proposed methodology was applied to a specific red grapevine cultivar, Aglianico cv., the most important cultivar in the Campania region for the production of Taurasi and Aglianico wines (“Denominazione di Origine Controllata” - DOC³ and “Denominazione di Origine Controllata e Garantita” - DOCG⁴).

Growth of the Aglianico grapevine cultivar on the 1103 Paulsen rootstocks (espalier system, cordon spur pruning) and its grape quality responses to crop water stress, had already been studied for different types of soils in the Campania region, in an area not so far from Valle Telesina (Bonfante et al., 2015b). Moreover, an analysis of quality grapes responses to climate change had been carried out in scenario A1B (ENSAMBLE, Van der Linden and Mitchell, 2009) by Bonfante et al. (2017).

The thermal index of Amerine and Winkler (1944) (A&W) was used as a thermal land use requirement (LUR_t). This is the thermal sum of average daily temperatures minus the zero vegetative of the grapevine (10 °C) in the period between 1 April and 31 October.

$$I(GDD) = \sum_{01/04}^{31/10} (Tm - 10) \quad (1)$$

where $I(GDD)$ is the A&W thermal index value expressed in growing degree-days (GDD); Tm is the average daily temperature and 10 is a constant representing the zero vegetative of the grapevine.

The index calculation only considers days when the average temperature was over 10 °C.

Using the available daily temperature from the Campania region weather station network, a regression analysis was made to identify the relation between A&W index and elevation of 37 weather stations inside of Campania region (representative of the 2000–2010 period). This (regional) regression was used to spatially distribute the A&W thermal index across the Taurasi and Valle Telesina areas. The obtained results were successively evaluated by means of Root Mean Square Error (RMSE) index applied to the weather stations inside of each study areas (4 regional weather stations for Valle Telesina, Telese, Solopaca, Guardia San Framondi and Castelvenere; 3 weather stations in Taurasi area: Mirabella Eclano, Montemarano and S. Paolina). Moreover, is important to stress that the reliability of applied procedure to spatialize the A&W index according to elevation, was already demonstrated, on a different climatic dataset (13 years, 1984–1996, in respectively 12 and 25 weather stations located both inside and in the surroundings outside of the study area) in Valle Telesina by Bonfante et al., 2011.

The LUR_t threshold for the Aglianico grapevine was determined combining the results obtained from a preliminary environmental analysis on A&W index variation inside of vineyard area of Taurasi region and the scientific literature (Scaglione et al., 2008). This preliminary analysis concerned an important territory of Campania region, Taurasi (near the Valle Telesina area), which is devoted to the production of DOCG Taurasi wine (based on Aglianico grapes) with a vineyard land use of about 6.2% (2399 ha) of the whole area (38,795 ha) (Fig. 3).

¹ Representative Concentration Pathway.

² With the term “functional Homogeneous Zones” (fHZs) are identified the zones inside of vineyard that have the same potential functionality (e.g. potential water stress), which affects the crop responses and the grapes quality. The term “functional” is employed in order to strengthen the soil–plant–climate functionality (Bonfante et al., 2015a).

³ “Denominazione di Origine Controllata” (DOC), which means “Demarcation of controlled production areas”.

⁴ “Denominazione di Origine Controllata e Garantita” (DOCG), which means “Demarcation of controlled and guaranteed production areas”. European label defines Italian label “DOC” and “DOCG” as PDO-Protected Designation of Origin.

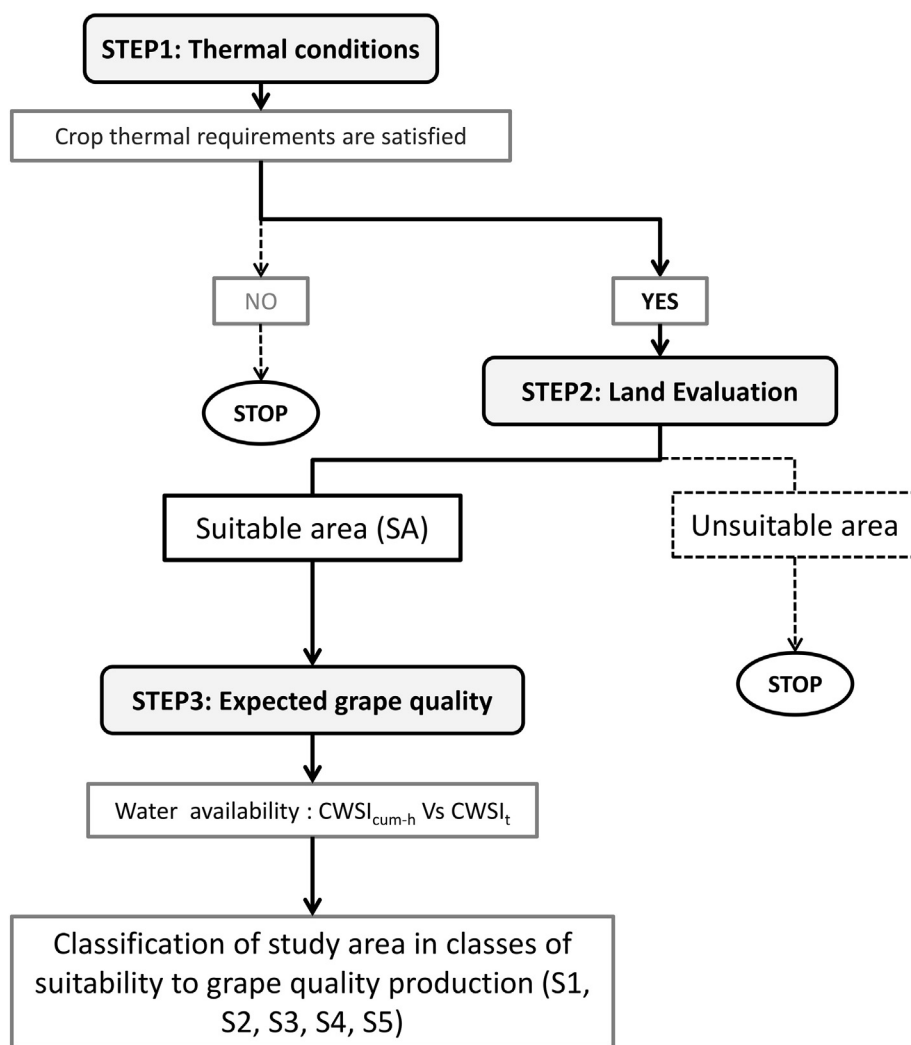


Fig. 1. The storyline of the Hybrid Land Evaluation system (HLES) applied (modified from Bonfante et al., 2015a). CWSI_{cum-h} = crop water stress index cumulated at harvest; CWSI_t = crop water stress index thresholds for specific grapevine cultivar and quality grapes.

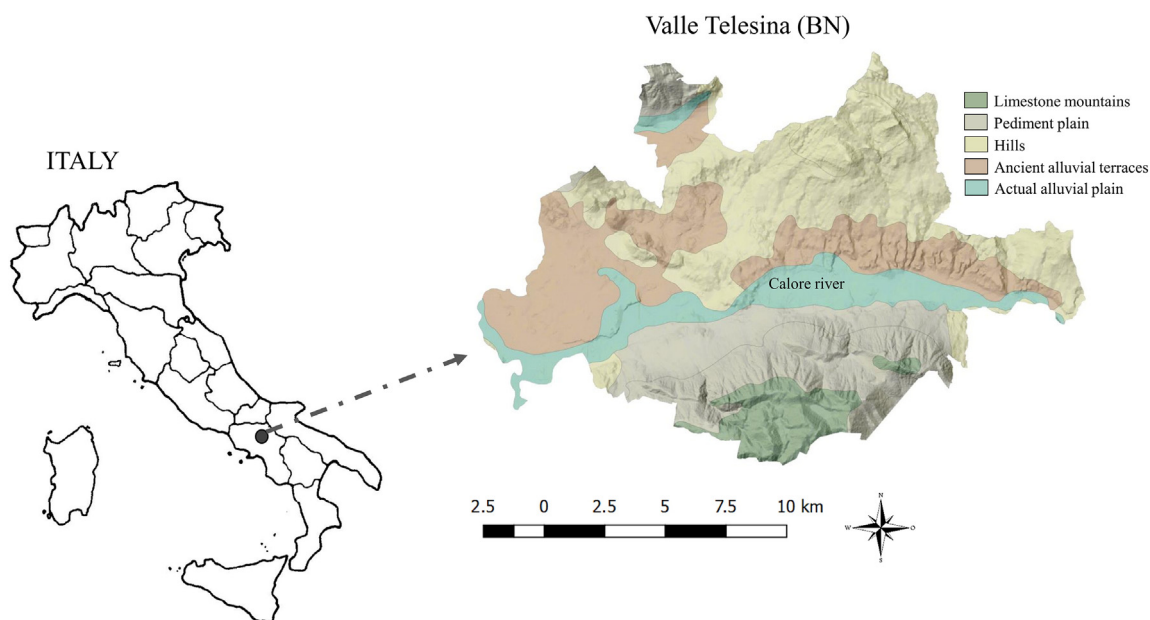


Fig. 2. The map of "Valle Telesina" (southern Italy) study area.

Finally, in accordance with Jones et al. (2012), an analysis of the extreme temperature events during the crop growing season was carried out for the future climate scenarios analysed, considering a threshold of -2.5°C for the minimum temperature and 35°C for the maximum.

2.4. Land evaluation for Aglianico cv. viticultural zoning

In scientific literature, there are several viticultural zoning procedures based on Land Evaluation approaches in which the physical environmental characteristics, able to influence the plant and the grape quality responses, are taken into account as Land Use Requirements (LUR_s) (Costantini and Bucelli, 2008; Priori et al., 2013; Vaudour and Shaw, 2017).

In our case study, focused on a specific grapevine cultivar, the use of generic physical LUR_s to identify the suitable areas for Aglianico cultivation could represent a limitation affecting the results of the approach. Therefore, here we have used a new procedure based on GIS environmental analysis to identify the specific physical LUR_s and corresponding thresholds for Aglianico cv.

The resulting data have been successively applied in STEP 2 to perform the Land Evaluation procedure in Valle Telesina.

The preliminary analysis and, as for the identification of thermal requirements, were realized in the Taurasi area (Fig. 3).

The basic assumption is that century-long trial and error processes have perfected the combination of cultivar/rootstock, soil, climate and management in traditional wine-growing regions, so that the local environment suits the grapevine thermal and moisture requirements, yielding high-quality grapes (Jones et al., 2004; Schultz and Jones, 2010).

Therefore, the environmental information used to define the specific LUR_s for Aglianico grapevine and successively realise the Land Evaluation procedure for Aglianico cv. in Valle Telesina (STEP 2) was:

- DTM (Digital Terrain Model; 5×5 m of resolution) of the Taurasi and Valle Telesina areas: these layers were used to derive the following spatial information: slope, aspect, Topographic Wetness Index (TWI) and potential insolation during the cropping season (1 April–15 October).
- Map of Land use of the Taurasi and Valle Telesina areas: the former was produced in 2009 by the Campania region and the latter in

2011 during the SOILCONSWEB LIFE + project (Terribile et al., 2015).

The spatial analysis out in GIS environment was performed using the Quantum GIS software and SAGA (<http://www.qgis.org>), applying the zonal statistic tool to identify the LUR_s thresholds in Taurasi area and the grid calculus tools (e.g. reclassify grid values) to classify the suitable area for Aglianico cultivation in Valle Telesina.

At the end of STEP 2 the study area is classified in two suitability classes: areas suitable and unsuitable for the cultivation of Aglianico cv.

Finally, because the applied land evaluation procedure doesn't take into account the current land use and then the presence of environmental land use limitation, the areas of Valle Telesina sensitive to land use change were omitted at the end of STEP 2. These areas are currently designated to grassland and woodland land use (*Quercus* spp., *Castanea sativa*, *Fagus sylvatica* and coniferous species), where a change in land use might favour processes of land degradation.

2.5. Simulation modelling

The Soil–Water–Atmosphere–Plant (SWAP) model (Kroes et al., 2008) was applied to solve the soil water balance and to calculate the CWSI for each soil identified as being suitable at STEP 2 of the applied dynamic viticultural zoning methodology.

SWAP is an integrated physically-based simulation model of water, solute and heat transport in the saturated–unsaturated zone in relation to crop growth. In this study, only the water flow module was used; it assumes 1-D vertical flow processes and calculates soil water flow through the Richards' equation. Soil water retention is described by the unimodal $\theta(h)$ relationship proposed by Van Genuchten (1980) and expressed in terms of effective saturation, S_e . Mualem's expression (Mualem, 1976) is applied to calculate relative hydraulic conductivity, K_r . Assuming $m = 1 - 1/n$, Van Genuchten (1980) obtained a closed-form analytical solution to predict K_r at a specified volumetric water content. The condition at the bottom boundary can be set in several ways (e.g. pressure head, water table height, fluxes, impermeable layer, unit gradient, etc.).

The upper boundary conditions of SWAP in agricultural crops are generally described by the potential evapotranspiration ET_0 , irrigation and daily precipitation. Therefore, the potential evapotranspiration is partitioned into potential soil evaporation, E_p , and potential transpiration, T_p , according to the LAI evolution, following the Ritchie (1972) approach.

The SWAP model had been previously used and tested in Italy and in the Campania Region (Bonfante et al., 2017; Bonfante et al., 2011) and is very often used in viticulture by different authors (Ben-Asher et al., 2006; Minacapilli et al., 2009; Rallo et al., 2011).

The crop parameters applied for simulation runs (e.g. Leaf Area Index, maximum rooting depth, general parameters, etc.) are reported in the supplementary material⁵ of Bonfante et al. (2017), in which two crop developments were considered, here reported as Low –PLV- and High –PHV- plant vigour.

The choice to simulate two different plant vigour was done in order to take into account the evidences raised from a previous project on Aglianico in Campania region (Zovisa project, three years of crop and soil monitoring), for which the same cultivar (and rootstock, 1103 Paulsen), can give different responses in terms of canopy development in different soils, under the same climate and crop management. Then on this base, the use of one crop model development could be not representative of the Aglianico cv. behaviour, and the representation in the simulation modelling application of its low and high canopy cover

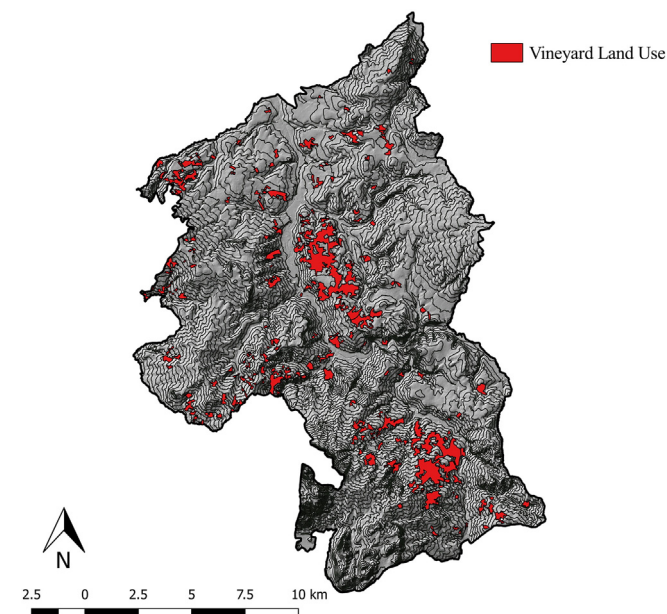


Fig. 3. The map of Taurasi DOCG area. The areas with vineyard land use are reported in red.

⁵ Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agry.2016.12.009>. Where CAM and CAL represent PHV and PLV respectively.

responses is necessary. Moreover, the use of two plant developments allows also to show the effects of a different canopy management on the climate change impact.

Soil information was derived from the existing soil map at 1:50,000 scale (Terribile et al., 1996) integrated with a recent soil survey which was realised within European LIFE + project SOILCONSWEB (Terribile et al., 2015). Soil hydraulic properties of 60 STUs, were derived by applying the pedotransfer function HYPRES (Wösten et al., 1999), preliminarily tested on lab measurement of the water retention and hydraulic conductivity of 17 soil profiles during the SOILCONSWEB project.

The dates of plant bud burst and harvesting was determined by means of temperature.

In particular: (i) the plant bud burst stage was defined by using an approach similar to that proposed for maize by Narciso et al. (1992), based on the occurrence of daily mean temperatures above 10 °C for at least 7 days; (ii) the date of harvesting (crop cycle length of each specific growing season) was defined in accordance with thermal sum requirements (expressed in terms of A&W GDD) that were identified in the previous studies on Aglianico cv. (2119 GDD applied to the Campania region to produce high quality wine), considering as a zero vegetative temperature value of 10 °C (Amerine and Winkler, 1944; Jones et al., 2005; Moriondo et al., 2013). Finally, the bottom boundary condition was set as a unit gradient.

Thus at STEP 3 of applied procedure, the SWAP simulation model was run to each STUs involved in the suitable areas at STEP 2, in order to evaluate $CWSI_{cum-h}$ behaviour in each climate scenario by considering two Aglianico plant vigour, PLV and PHV.

2.6. The hydrological indicator: Crop Water Stress Index (CWSI)

In literature, different variables and approaches could be applied to develop a proper water stress index. However, as reported by Kozak et al. (2006), the use of transpiration information is realistically more variable for defining the crop water stress. In our approach, to simulate the soil water balance, we used a simulation model (SWAP) based on the Richards' equation. This model is very different from the one applied by Kozak et al. (2006). It is very robust for stimulating the soil water balance and, moreover, it has previously been used and tested in Italy and in the same region of Campania (Bonfante et al., 2015b; Bonfante et al., 2017; Bonfante et al., 2011).

The applied daily crop water stress index (CWSI) was defined as follows:

$$CWSI = \left[1 - \left(\frac{T_r}{T_p} \right) \right] \cdot 100 \quad (2)$$

where T_r is the actual daily plant transpiration (plant water uptake) and T_p is the potential daily plant transpiration.

The sum of daily CWSI over the required period constitutes the cumulated stress $CWSI_{cum}$:

$$CWSI_{cum} = \frac{\left[\int_{t_1}^{t_2} 1 - \left(\frac{T_r}{T_p} \right) \cdot dt \right]}{(t_2 - t_1)} \cdot 100 \quad (3)$$

By changing the integration time (t_1 and t_2), the application of this index enables estimation of plant water stress at different stages of crop growth (shoot growth, flowering, berry formation, berry ripening etc.) (Bonfante et al., 2015b; Bonfante et al., 2017; Bonfante et al., 2011; Terribile et al., 2017).

2.7. Grape quality classes and suitability classes to Aglianico high quality grapes production

The CWSI calculated through application of the simulation model, to each climate scenario, plant vigour and soil suitable at STEP 2 will be used to evaluate expected Aglianico grape quality.

Work indicating the relationship between CWSI and Aglianico grape quality was recently published by Bonfante et al. (2017) (Table 1), who identified CWSI thresholds at harvest ($CWSI_{cum-h}$) for four different Aglianico grape quality classes as the following:

1. Ultra Quality Grapes (UQG) to obtain ultra-quality wines: $CWSI_{cum-h}$ values at between 10 and 15%;
2. Standard Quality Grapes (SQG), which could easily be processed to obtain ultra-quality wines and standard-quality wines respectively: $CWSI_{cum-h}$ values between 5 and 10%;
3. Low Quality Grapes (LQG), which cannot be used to produce good quality wines: $CWSI_{cum-h}$ values below 5%;
4. UQG with uncertainty (UQG_u): for which the expected results cannot be defined with certainty $CWSI_{cum-h} > 15\%$.

To the latter category, the maximum value was fixed at 30% of $CWSI_{cum-h}$. Above this, severe plant water stress will occur, which will make it necessary to consider introduction of irrigation management (in the current rainfed crop system) to preserve plant safety and to produce quality grapes.

Starting from the results of the analysis of the expected grape quality in each STU, the areas involved at STEP 3 are classified into five classes of suitability (S1, S2, S3, S4, S5) towards high quality Aglianico grapes production:

- S1 (fHZs resilient to UQG production): areas where, given a specific climate scenario, the average probability of producing UQG is $>20\%$ and the sum of the average probabilities for UQG and UQG_u is $>60\%$.
- S2 (fHZs with high uncertainty regarding the achievability of UQG): areas where, given a specific climate scenario, the average probability of producing UQG_u is $>60\%$ and UQG $>10\%$ and $<20\%$.
- S3 (fHZs with high sensitivity to climate change): areas where the probability of quality grape production is highly variable during the climate scenario time periods, but always orientated towards UQG.
- S4 (fHZs with a severely limited water availability for which irrigation is required): areas where the probability of high crop water stress is $>80\%$ and a controlled irrigation management can lead to a UQG production.
- S5 (fHZs resilient to LQG production): areas where, given a specific climate scenario, the average probability of producing LQG is $>30\%$ and the sum of the average probabilities for LQG and SQG is $>70\%$.

2.8. Climate information

The weather stations (37) of the Campania region network were used to determine the local relationship between the A&W index and elevation, in order to define the specific LUR_t threshold for Aglianico cv.

Future climate scenarios were obtained by using the high resolution regional climate model (RCM) COSMO-CLM (Rockel et al., 2008), with a configuration employing a spatial resolution of 0.0715° (about 8 km), which was optimised over the Italian area. The validations performed showed that these model data agree closely with different regional high-resolution observational datasets, in terms of both average temperature and precipitation in Buccignani et al. (2015) and in terms of extreme events in Zollo et al. (2015).

In particular, two different simulations were performed by employing two standard IPCC (Intergovernmental Panel on Climate Change) RCP 4.5 and RCP 8.5 greenhouse gas (GHG) concentrations (Meinshausen et al., 2011); respectively the RCP 4.5 scenario exhibits a stabilisation in GHG emissions, while the RCP 8.5 has a rapidly

Table 1

Range of principal grape characteristics affecting the Aglianico grape quality and the corresponding values of CWSI (Bonfante et al., 2017).

	LQG	SQG/WPQG	UQG
CWSI (%)	<5	5–10	10–15
Sugar (°Brix)	<22	22–23	23–24
pH	<3	3–3.6	<7.5
Ac. Tot (g/L)	>8		
Weight 100 Berries (g)	>225	225–190	<190
Vol 100 Berries (mL)	>215	215–190	<190
Colour intensity of skin extract	<4.3	5–4.3	>5
Colour hue of skin extract	0.5	0.5	≤0.5
Total anthocyanins (mg kg ⁻¹)	<450	450–600	>600
Tot. Polyphenols skin (mg kg ⁻¹)	<1700	1600–2000	>2000
Tot. Polyphenols seed (mg kg ⁻¹)	>1700	>1700	<1700
Tot. Tannins skin (mg kg ⁻¹)	<2300	2300–2600	>2600
Tot. Tannins seed (mg kg ⁻¹)	<1700	1500–1800	>1700

increasing GHG concentration. Initial and boundary conditions for running RCM simulations with COSMO-CLM were provided by the general circulation model CMCC-CM (Scoccimarro et al., 2011), whose atmospheric component (ECHAM5) has a horizontal resolution of about 85 km. The two simulations performed cover the period from 1971 to 2100; more specifically, the CMIP5 historical experiment (based on historical greenhouse gas concentrations) was used for the period 1971–2005 (Reference Climate scenario - RC), while, for the period 2006–2100, two different simulations were performed using the IPCC scenarios mentioned.

3. Results and discussion

3.1. Preliminary environmental analysis to establish Land Use requirement with respect to procedure applied: definition of environmental land use requirements (LUR_e) and thermal requirement (LUR_t) thresholds for the Aglianico grapevine

The environmental and thermal Aglianico requirements were derived from DTM and climate information analysis of vineyard areas in the Taurasi region.

The results of LUR_e analysis (Table 2) indicate that the areas under Aglianico grapevine cultivation have an average value of slope of 18%, a prevalent south-east exposure with an average total potential insolation of 1453 (kwh m⁻²) and an average TWI of 3.4.

In order to identify the LUR_t of Aglianico, a regression analysis between the average values of the A&W index, obtained in the Campania region was performed and used to produce a representative map of the A&W index of the Taurasi area (Fig. 4).

The RMSE of spatialized A&W index on Taurasi area was 89 GDD. Moreover, the average error of data spatialized over the whole Campania region was of -1% (± 8).

In the Taurasi area, the average value of the A&W index ranges from 1546 to 2199 GDD while the value ranges from 1600 to 2152 GDD within the vineyard areas. This range is not so distant from data reported in the literature, in particular Scaglione et al., (2008) showed a range between 1754 and 1854 GDD for Aglianico, while, on a farm within the Taurasi Area devoted to high quality Aglianico wine production, Bonfante et al. (2015b, 2017) more recently identified an average value of the A&W index at harvest of 2119 (± 83) GDD (this value

was used to identify the harvesting date in the simulation modelling application at STEP 3), with a maximum seasonal value of the A&W index of 2350 GDD on 31st October.

By combining the results of the Taurasi environmental analysis with data reported in the literature, the range of the A&W index identified as LUR_t for Aglianico cv. was defined as between 1754 and 2350 GDD.

In Table 2, the complete list of the identified land use requirements thresholds for Aglianico grapevine is reported and these are then used to determine the area suitable for Aglianico grapevine cultivation in Valle Telesina (STEP 2 of applied methodology, Fig. 1).

The ranges of Aglianico Land Use Requirements reflect the Aglianico genotype plasticity to the environmental variability (A&W, aspect and solar radiation) and farmer needs for cultivation (slope lower than 30% to allow the mechanization of productive processes).

3.2. STEP 1: Evaluation of thermal crop land use requirements (LUR_t) in the analysed climate scenarios

In the first step, analysis was made of RC (1971–2005) and two future climate scenarios, RCP 4.5 and 8.5 divided into three different time periods (2010–2040, 2040–2070 and 2070–2100).

The analysis of temperatures showed an increase of approximately one and two degrees Celsius in the RCP 4.5 and 8.5 respectively every 30 years from RC to 2100.

The differences in temperature between RC and 2070–2100 showed an average increase of minimum and maximum temperatures of 3.6 and 3.0 °C respectively for RCP 4.5 and about 6.2° (for both min and max; significant at $p < 0.01$) for RCP 8.5. As regards extreme temperature events, the probability of temperatures below -2.5 °C was 2% for RCP 4.5 and 1% for RCP 8.5, and 2% and 5% for values exceeding 35 °C. In both future scenarios, most of the extreme events (65%) related to high temperature, occurring mostly in the 2070–2100 time period. Moreover, precipitation regimes also showed very different features compared with those for the reference period. This behaviour is in line with results reported in Bucchignani et al., 2015 and Zollo et al., 2015.

The change in the average pattern and the increase in extreme events are expected to be among the most important effects of the increase in average global temperatures (higher for the 2071–2100 time period and considering the IPCC RCP 8.5 scenario) as a consequence of the higher concentration of GHG in the atmosphere (IPCC, 2015).

Table 2Environmental (LUR_e) and thermal land use requirements (LUR_t) for Aglianico grapevine.

Environmental characteristics	min	Optimal/mean	max
Amerine & Winkler (GDD)	1754	1960	2350
Slope (%)	0	18	27
Aspect (°N)	0	171	278
Topographic Wetness Index (TWI)	2.1	3.4	5.3
Tot. Pot. Insolation (1 Apr–31 Oct) (kwh m ⁻²)	1079	1410	1577

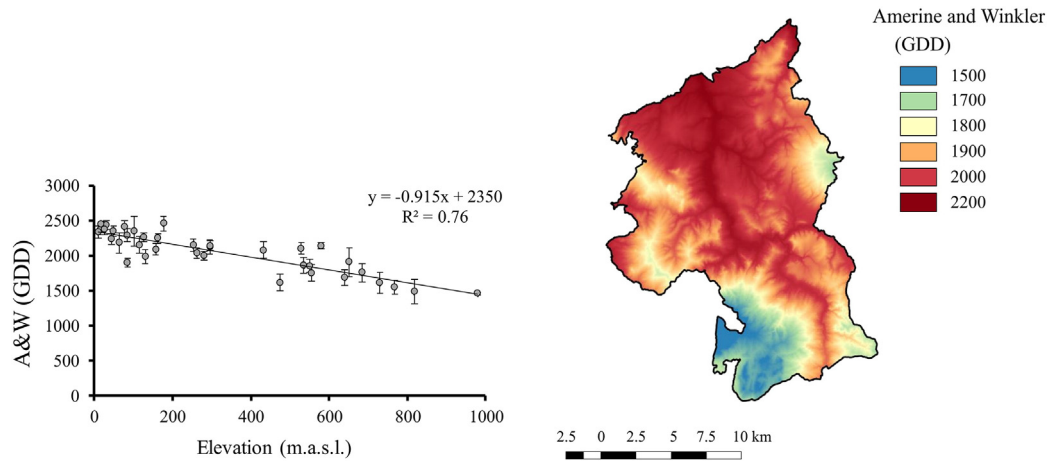


Fig. 4. The relationship between the average Amerine and Winkler thermal index values (A&W) and elevation (a), and the spatialized A&W index within the Taurasi area (b).

In Fig. 5, the cumulated rainfall amount during the plant growing season (1th April–31th October) in the analysed climate scenarios and their respective time periods are shown.

The average cumulated rainfall will decrease (significant at $p < 0.01$) from RC to 2070–2100 by about 22% and 38% for RCP 4.5 and 8.5 respectively.

The A&W index was calculated for each year of analysed climate scenarios and the results are reported in terms of a probability density function (PDF) (Fig. 6).

The A&W index showed a high variability in both RCP 4.5 and RCP 8.5 scenarios, with a clear shifting of distribution towards higher values (on the right of the graph). It is particularly interesting to note how the shape of curves for 2010–2040 are similar across the RCP scenarios, while, in the other time periods, the shapes and the standard deviation were very different. In the RCP 8.5, the highest values of the A&W index occur with a small overlap with the highest values of RC. Moreover, the highest values of RCP 4.5 2070–2100 fall near the mean value of RCP 8.5 2070–2100. Indeed, the distribution of the RCP 4.5 2070–2100 is more similar (in terms of mean) to the RCP 8.5 2040–2070 distribution. The differences obtained between the RC and future climate scenarios are

significant ($p < 0.01$) also considering the error of model applied for the A&W index spatialization in Valle Telesina (average error of model prediction of 2% (± 8)). Moreover, it is also important to stress that the accuracy of temperature prediction of high-resolution simulations used for future climate scenarios was good with a low bias, statistically significant and consistent with others obtained with both global and regional models, for different emission scenarios (Bucchignani et al., 2015).

In order to identify an area of Valle Telesina that is able to satisfy the Aglianico LUR_t for each climate scenario and time period, the average value of A&W has been spatialized within the study area by means of the relationship between the A&W index and elevation identified for the Campania region (Fig. 7). The maps obtained were reclassified by applying the identified LUR_t for Aglianico cv. (1754–2350 GDD), indicating the areas where the Aglianico thermal requirement is satisfied for each RCP scenario and time period (maps of thermal suitable area, Fig. 7).

As reported in Table 3, the suitable area for Aglianico cultivation is at a maximum, under both climate scenarios, in the 2010–2040 time period (75% and 77% in RCP 4.5 and 8.5 respectively), with a marked reduction up until 2100, which is more evident in RCP 8.5 (24% vs 5%, RCP 4.5

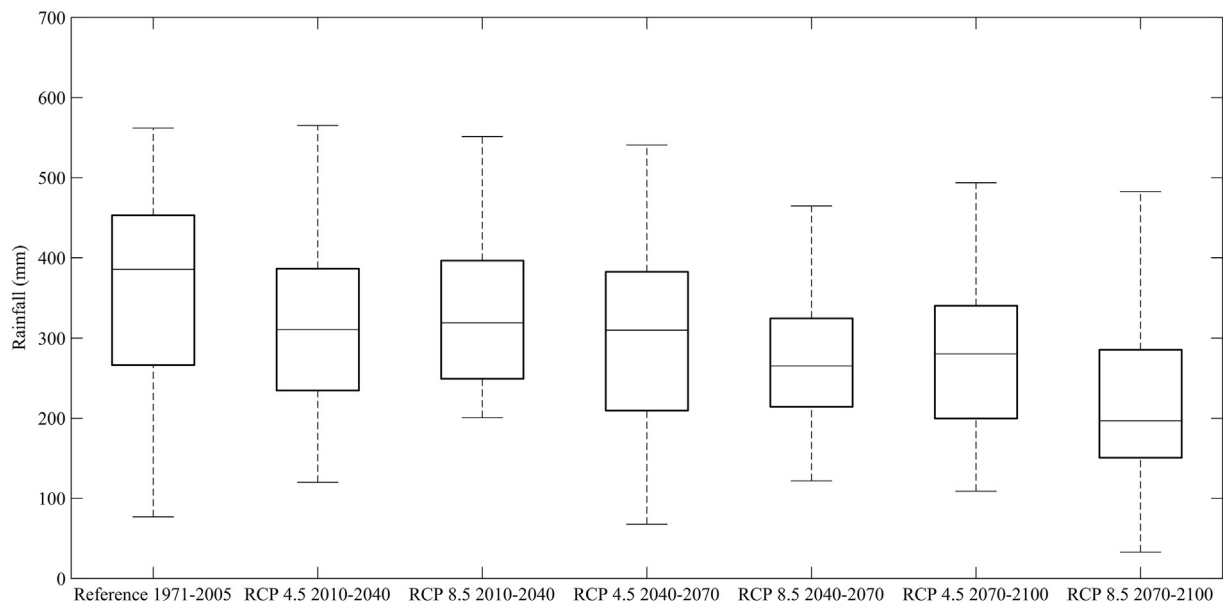


Fig. 5. Boxplot of cumulated rainfall during the grapevine growing season (1th April–31th October) in the analysed climate scenarios and their respective time periods (2010–2040, 2040–2070 and 2070–2100).

and 8.5). It is interesting to observe from the results that the suitable RCP 4.5 area during the 2070–2100 period is similar to that obtained for RCP 8.5 during the 2040–2070 period. This means that an evident differentiation between the two climate scenarios, for the Aglianico LUR, starts after the year 2040, in accordance with the fact that uncertainty between the scenario models is expected to be low until after 2040 (IPCC, 2014).

3.3. STEP 2: Land evaluation for Aglianico cultivation

The environmental LUR_s identified for Aglianico cv, slope, aspect, TWI and potential solar radiation — 1 April to 31 October (reported in paragraph 3.1) and their ranges (Table 1), were used to evaluate the environmentally suitable areas of Valle Telesina for Aglianico grapevine cultivation. It emerged from the analysis that 5145 ha of Valle Telesina (about 23% of study area) are suitable for Aglianico cultivation.

The maps of thermally suitable areas, obtained from the A&W index analysis in STEP 1 (Fig. 7) and the environmental suitable areas map, were cross-referenced to identify a suitable area for Aglianico cultivation (SAA) during the three climate scenarios and their relative time periods (Fig. 8).

In the 2010–2040 period, the SAA increase by 13% in both RCP scenarios if compared with the reference period (1971–2010). However, moving towards 2100, their surface area will shrink by 0.3% in RCP 8.5, with a similar dimension to the reference climate in RCP 4.5 (1760 ha) in 2040–2070. Moreover, in the 2010–2040 period, the SAA identified are very similar in RCP 4.5 and 8.5 and overlap by 99% of the surface. It is interesting to report that in the 2040–2070 and 2070–2100 periods, the omitted areas as sensitive to land use change,

represent the 14% and 35% of SAA of the former and of 38% and 100% in the latter (RCP 4.5 and 8.5 respectively).

3.4. STEP 3: Expected Aglianico grape quality

From the Valle Telesina soil map, the STU_s and their soil characteristics were associated with the identified suitable areas for Aglianico cultivation at STEP 2.

The number and the surface areas of STU_s suitable varied very much during the three climate scenarios in the analysed time periods, in accordance with the results obtained at STEP 2.

Indeed, the SAA surface area for the Aglianico cultivation changing over time, and thus the STUs involved, this can be considered the first effect of climate change on the viticultural sector in the study area (shifting of cultivation due to climate change). Therefore, an evaluation of how CC affects the dimensions of those STU involved in the SAA areas was made.

In the SAA of RC, 25 STUs were identified. These were also recognised in the future climate scenarios RCP 4.5 and 8.5, with a clear increase in surface area in the first time period (2010–2040) of 107% and 101% of the total RC STUs surface area in RCP 4.5 and 8.5 respectively, with a maximum increment in the VIV1 STU (4069% compared with the RC). Furthermore, in the subsequent time periods, the STU surface of RC would diminish by 46% and 93% (2040–2070) and 94% and 100% (2070–2100) in RCP 4.5 and 8.5 respectively.

The variation in CWSI_{cum-h} and its effects on expected grape quality in the STUs of the RC period involved in the future climate scenarios is shown in Fig. 9 in terms of the variation compared with the RC in both RCP 4.5 and 8.5 future climate scenarios.

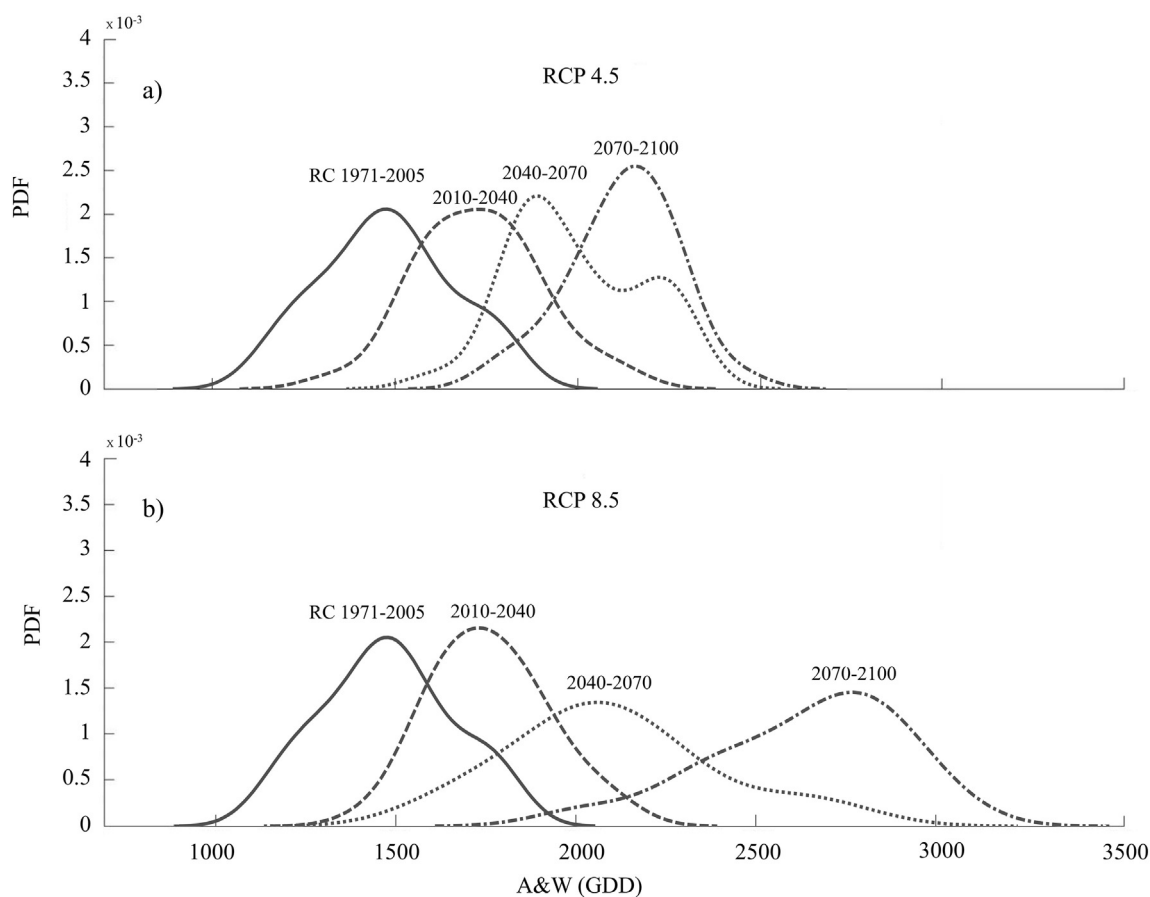


Fig. 6. Probability Density Function (PDF) of the Amerine and Winkler index in the analysed climate scenarios RC (1971–2005), RCP 4.5 (a) and 8.5 (b) and their time periods (2010–2040, 2040–2070, 2070–2100).

Table 3
Suitable areas of Valle Telesina obtained in STEP 1 and 2.

Climate scenario		A&W suitable areas (STEP 1)		Suitable areas derived from A&W and LE intersection (STEP 1 + STEP 2)		Suitable areas derived from A&W and LE intersection (STEP 1 + STEP 2) - sensible areas to change of Land Use ^a	
		(ha)	(%) ^b	(ha)	(%) ^b	(ha)	(%) ^b
RC	1971–2010	7458	36.9	1822	9.0	1822	9.0
RCP 4.5	2010–2040	15,231	75.3	4401	21.8	3954	19.6
	2040–2070	8695	43.0	2055	10.2	1760	8.7
	2070–2100	4895	24.2	576	2.8	359	1.8
RCP 8.5	2010–2040	15,544	76.9	4432	21.9	3979	19.7
	2040–2070	5169	25.6	636	3.1	414	2.0
	2070–2100	1079	5.3	62	0.3	0	0.0

^a Grassland, woodland (*Quercus* spp., *Castanea sativa*, *Fagus sylvatica* and coniferous species).

^b Percent of study area.

In RCP 4.5 (PLV and PHV), the increase in $CWSI_{cum-h}$ over the STUs was 17% compared with the RC, while the increase was 36% for RCP 8.5. Moreover, in the 2040–2070 time period, the RCP 4.5 PLV and PHV results behaved very similarly (72% and 61% for PLV and PHV respectively). The highest variability of $CWSI_{cum-h}$ was shown in the RCP 8.5 PHV plant, where there was 100% variation.

Starting from the $CWSI_{cum-h}$ results, the analysis of the expected classes of grape quality and their probability in each STU involved in the RC and future climate scenarios was carried out and the involved SAA were classified into the five classes of suitability (S1, S2, S3, S4, S5) for Aglianico quality grape production (see M&M).

The results of this analysis are reported in Table 4, where, for each class of suitability for Aglianico grape quality production, in accordance with the combination of future climate scenarios and plant vigour (PLV and PHV), the relative STUs of RC climate (number and name, surface area in RC and in the future time periods) and their dimensions are reported.

The conducted analysis shows that only three STUs (CAN1 – Calciustepts, CER1 – Haplustepts and SRL1 – Haplustepts) are classified as S1 in RCP 4.5 (PLV) and two of these maintain their suitability class (CAN1 and CER1) in RCP 8.5 (PLV) and RCP 4.5 (PHL).

- The S1 class surface (fHZs resilient to UQG production) area was at a maximum in the first time period (2010–2040) in both future climate

scenarios (from 274 ha to 175 ha, equal to 6 and 15 times the S1 RC surface area respectively) and at a minimum in 2070–2100 (from 6 ha to 0, the first case being equal to half of the S1 RC surface area), except for in RCP 8.5 (PHV) for which no STUs were classified as S1.

- The S2 class surface (fHZs with high uncertainty on the UQG achievable) was at a maximum in RCP 4.5 (PLV) (374 ha, equal to 4 times the RC surface area) during the first time period (2010–2040) involving four STUs. Only the S2 surface was present for all time periods in RCP 4.5 (PLV). Indeed, its maximum surface diminished in RCP 4.5 (PHV) and RCP 8.5 (PLV) to 99 (3 times the S2 RC surface) and 35 ha (equal to the S2 RC surface) in 2010–2040 (only one STU involved), with no surface area as early as 2040–2070. Moreover, it is interesting to note that, in RCP 8.5 (PHV), some of the STUs involved are classified as S1 in the other simulation scenarios. In this case, the S2 surface was at a maximum in 2010–2040 (248 ha, equal to 3 times the S2 RC surface).
- The S3 class surface (fHZs with high sensitivity to CC) was at a maximum in the RCP 4.5 (PHV) scenario in first time period (2010–2040) with 1033 ha (about twice the S3 RC surface) and at a minimum for all simulated scenarios in the 2070–2100 period (from 6 ha to 0 ha). In the RCP 4.5 scenario (PLV and PHV), the S3 areas were involved over all time periods, while they were not always present in RCP 8.5. Finally, in RCP 4.5 (PLV), four STUs were involved in the S3 areas while eight were identified in the other scenarios.

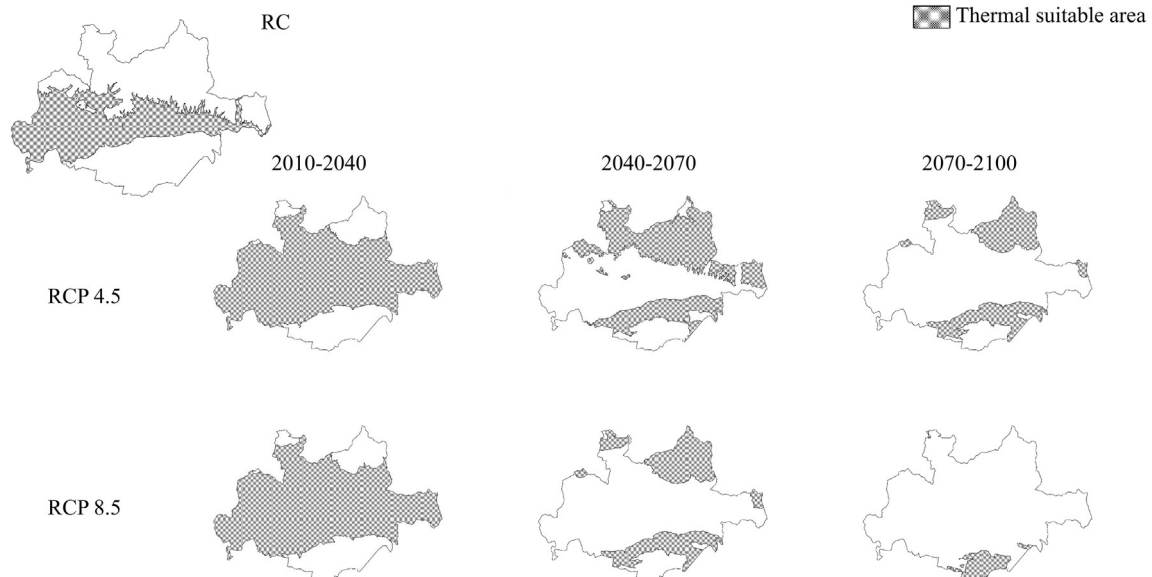


Fig. 7. Maps of the suitable thermal area of Valle Telesina as expected for the reference climate (RC) and the two climate scenarios analysed, RCP 4.5 and 8.5, and the three time periods (2010–2040, 2040–2070 and 2070–2100).

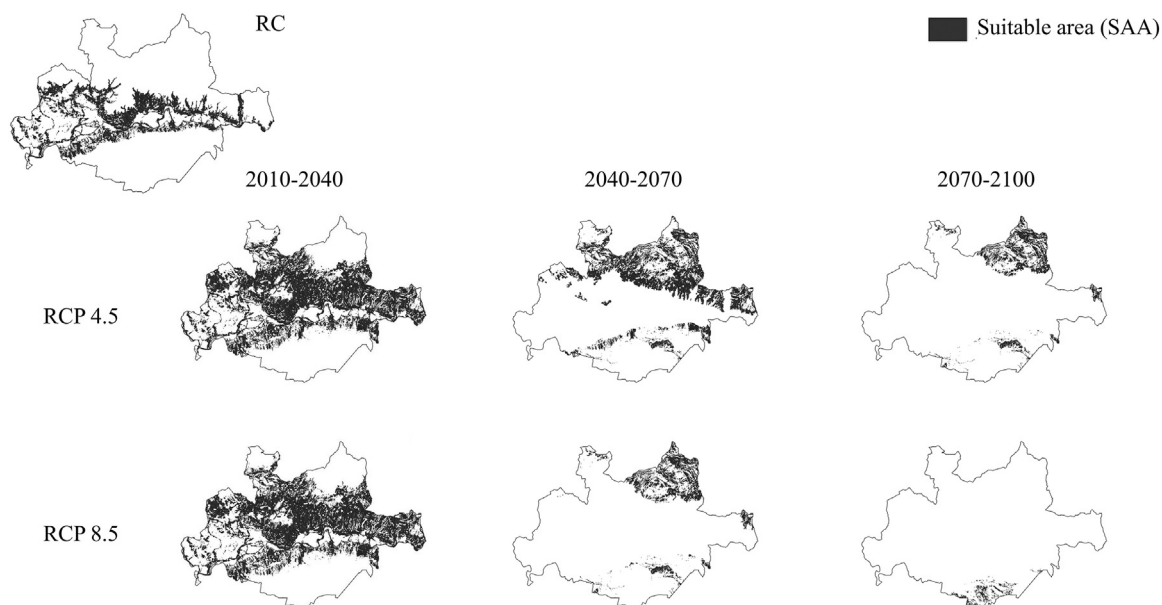


Fig. 8. The maps of suitable areas for Aglianico cultivation (SAA) during the three climate scenarios: reference climate (RC), RCP 4.5 and 8.5 and their respective time periods.

- The S4 class surface (fHZs with a severe water availability limitation, for which the irrigation is required) is the most common class in Valle Telesina in each simulated scenario, involving, on average, 13 STUs for a maximum surface area of 2038 ha in the first time period (2010–2040) of RCP 8.5 (PHV). The minimum S4 surface occurred during the 2070–2100 time period (from 55 ha to 0 ha). In the RCP 4.5 scenario (PLV and PHV), the S4 areas were involved over all time periods, while they were not always present in RCP 8.5.
- Finally, the S5 class surface (fHZs resilient to LQG production) was the least common class in Valle Telesina in each simulated scenario, involving only one STU for a maximum surface of 262 ha in the first time period (2010–2040) of RCP 4.5 (PHV) (the RCP 4.5. PLV is very similar). The minimum S5 surface occurred in the 2040–2070 time period (from 1 ha to 0 ha). In the RCP 4.5 (PHV) scenario, the S5 areas were not present over all time periods.

It is important to stress that the STU involved in the S5 areas was the same in all the simulated scenarios. Therefore, this STU (SPE1;

Ustivitrands) can be considered as a case of terroir resilience to LQG production.

4. Discussion

The future climate scenarios analysed will bring an increase in temperature and a decrease in rainfall during the grapevine cropping season (1 April–31 October) in the study area. The expected future changes in temperature will determine: i) a shifting of suitable areas satisfying the Aglianico thermal requirement, with a reduction in suitable surface area (75% and 77% in RCP 4.5 and 8.5 in the 2010–2040 time period versus 24% vs 5%, RCP 4.5 and 8.5, in the 2100), ii) a general anticipation of harvesting dates by about 7–10 days, iii) an increase in expected evapotranspiration demand.

These results, and, in particular, the zeroing of SAA, make it imperative to find solutions that will allow the continuation of Aglianico cultivation in the study area, emphasising that the whole of the Valle Telesina viticultural sector is in danger in the near future.

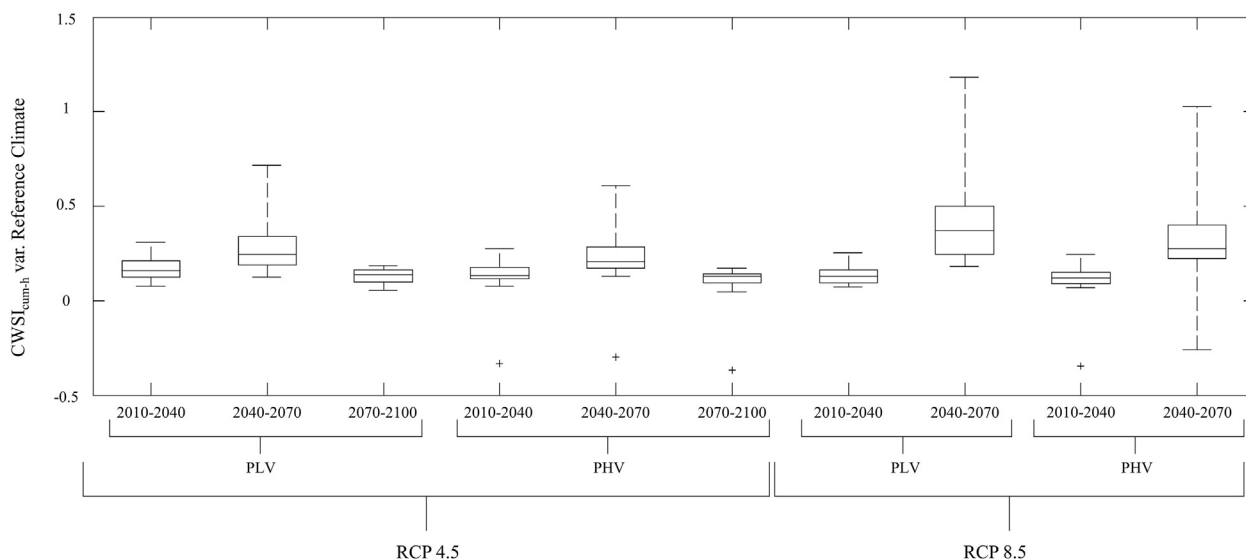


Fig. 9. Boxplot of the variation in $CWSI_{cum-h}$ between the reference climate (RC) and future climate scenarios and their time periods (2010–40, 2040–70, 2070–100) for each STU involved in the RC considering both simulated Aglianico plant vigour (PLV and PHV).

Table 4

The classification of SAA areas of Valle Telesina in terms of suitability classes for grape quality production for Aglianico cv. under future climate scenarios.

Class of suitability	Info	RCP 4.5		RCP 8.5	
		PLV	PHV	PLV	PHV
S1 (fHZs resilient to UQG production)	N° of STU (name)	3; (CAN1, CER1; SLR1)	2; (CAN1, CER1)	2; (CAN1, CER1)	–
	Surface at RC (ha)	46	12	12	
	Max surface (ha; time period)	274 (2010–2040)	176 (2010–2040)	175 (2010–2040)	
	Min surface (ha; time period)	6 (2070–2100)	6 (2070–100)	0 (2070–100)	
S2 (fHZs with high uncertainty on the UQG achievable)	N° of STU (name)	4; (PAO1, POC1, CES1/TOI1; CAL1)	1; (SRL1)	1; (SRL1)	3; (CAN1, CER1; SPE1)
	Surface at RC (ha)	98	34	34	77
	Max surface (ha; time period)	374 (2010–2040)	99 (2010–2040)	35 (2010–2040)	248 (2010–2040)
	Min surface (ha; time period)	19 (2070–2100)	0 (2040–2070)	0 (2040–2070)	0 (2070–2100)
S3 (fHZs with high sensitivity to CC)	N° of STU (name)	4; (LAT1, PEL1, PEZ1; TAS1)	8; (CAL1, CES1/TOI1, LAT1, PAO1, PEL1, PEZ1, POC1, TAS1)	8; (CAL1, CES1/TOI1, LAT1, PAO1, PEL1, PEZ1, POC1, TAS1)	8; (CAL1, CES1/TOI1, LAT1, PAO1, PEL1, POC1, SRL1, TAS1)
	Surface at RC (ha)	379	571	571	514
	Max surface (ha; time period)	379 (ref. Climate)	1033 (2010–2040)	980 (2010–2040)	822 (2010–2040)
	Min surface (ha; time period)	6 (2070–2100)	5 (2070–2100)	0 (2070–2100)	0 (2070–2100)
S4 (fHZs with a severe water availability limitation, for which the irrigation is required)	N° of STU (name)	13; (VIV1, SOL1, PRT1/LAR1, PET1, MAM1, MAG1/PET1, MAG1, LAC1/TOI1, CRU1/IMP1, COD1, CDA1/MON1, CAS1/LAM1, BOC1)	13; (VIV1, SOL1, PRT1/LAR1, PET1, MAM1, MAG1/PET1, MAG1, LAC1/TOI1, CRU1/IMP1, COD1, CDA1/MON1, CAS1/LAM1, BOC1)	13; (VIV1, SOL1, PRT1/LAR1, PET1, MAM1, MAG1/PET1, MAG1, LAC1/TOI1, CRU1/IMP1, COD1, CDA1/MON1, CAS1/LAM1, BOC1)	14; (VIV1, SOL1, PRT1/LAR1, PEZ1, PET1, MAM1, MAG1/PET1, MAG1, LAC1/TOI1, CRU1/IMP1, COD1, CDA1/MON1, CAS1/LAM1, BOC1)
	Surface at RC (ha)	863	863	863	953
	Max surface (ha; time period)	1627 (2010–2040)	1627 (2010–2040)	1845 (2010–2040)	2038 (2010–2040)
	Min surface (ha; time period)	55 (2070–2100)	55 (2070–2100)	0 (2070–2100)	0 (2070–2100)
S5 (fHZs resilient to LQG production)	N° of STU (name)	1; (SPE1)	1; (SPE1)	1; (SPE1)	–
	Surface at RC (ha)	65	66	66	
	Max surface (ha; time period)	261 (2010–2040)	262 (2010–2040)	72 (2010–2040)	
	Min surface (ha; time period)	0 (2040–2070)	1 (2040–2070)	0 (2040–2070)	

*PLV = plant low vigour; **PHV = plant high vigour; RC = reference climate (1971–2005).

Thus, in order to guarantee the future of Aglianico cultivation in the study area after 2040, a genetic selection of new cultivars that are able to adapt to high values of the A&W index could be needed. Indeed, the reduction in the Aglianico crop growth cycle brought about by future climate conditions will not ensure the appropriate ripening process to achieve the grapes organoleptic characteristics, so affecting wine quality (e.g. in terms of the flavour precursors, grape colour...etc.).

The alternative solution would be to identify a grapevine cultivar that can adapt to the expected A&W values (e.g. Aleatico, Barbera, Refosco, Ruby Cabernet, Touriga... etc. with A&W needs of between 2200 and 3300 GDD; [Fregoni, 2005](#)) and which also meets future wine consumers' tastes on both the domestic and foreign markets. This would be a viable, concrete solution that would ensure the future resilience of viticulture in Valle Telesina.

The decrease in rainfall and the increase in evapotranspiration demand lead to a future increase in CWSI in all the soils in the study area with a direct effect on expected grape quality.

On the basis of the analysis realised in STEP 3, three principal considerations can be made: 1) the most suitable S1 areas, able to maintain their status of excellent terroir orientated towards UQG, and, therefore, best able to express the concept of terroir resilience for Aglianico production, currently constitute, at most, 2% of the SAA in the study area (only referring to 2–3 types of soil); 2) it is clear that an irrigation practice must be introduced into grapevine cultivation in Valle Telesina in the near future, in order to preserve this important local agricultural sector (the principal crops cultivated in Valle Telesina are grapevines and olive trees) and achieve quality grape production (in the Aglianico case, this means producing UQG in areas that could represent 41% of the total SAA available in 2010–2040); 3) in the first time period (2010–2040), the future climate conditions (RCP 4.5 and 8.5) could be considered an opportunity to increase, compared with the reference climate, the available surface area capable of producing Aglianico UQG in Valle Telesina (see supplementary material). However, when the expected CO₂ concentration is considered to be high (RCP 8.5), the benefits for the cultivation of Aglianico cv., as well as the area suitable, will decrease.

The areas classified as S1, clearly represent a case in which the soil is able to mitigate the future climate constraints, maintaining a good grape quality production. On the contrary, in the areas classified as S4 the soil is not able to mitigate the climate change effects on grape quality. In the case of S5 areas, the combination of an increase in climate constrictions (RCP 8.5) and plant vigour (PHV represents an increase in canopy cover - LAI - compared with PLV) allows an improvement in expected grape quality from LQG to UQG (from S5 class to S2 class). On the other hand, the increase of climate constriction and plant vigour have negative effects on soils classified as S1 which pass into the S2 class.

The proposed methodology was applied to Valle Telesina for a specific vineyard (Aglianico, currently cultivated in study area), although the results from the first two steps could be extended to different vine cultivars currently cultivated in the study area (e.g. Malvasia di Candia, which has a similar thermal requirement to Aglianico, [Scaglione et al., 2008](#)). This was confirmed, in the supplemental material, by the overlapping of boundaries of SAA and current vineyard land use (Fig. 1s) as result from the applied threshold of the A&W index for Aglianico cv., which is similar to the value necessary to produce quality wine, (A&W of 1900–2200 GDD, [Fregoni, 2005](#)) and, thus, typical of regions that are devoted to quality wine production as the Valle Telesina is.

This last consideration reflects the nature of the proposed approach, which can be used for different plant species and cultivars (it was previously used for maize, [Bonfante et al., 2015](#)) with different levels of analysis detail, in accordance with the available knowledge on the evaluated plant's adaptation to climate change (e.g. land use requirements, crop response to water availability, crop parameter input for simulation modelling).

The results of this case study (viticulture on a district scale) represent an excellent example of support for local environmental planning,

in which several local actors might be involved (Environmental planners, Municipalities, Agricultural consortiums), producing local social benefits.

5. Conclusion

The methodology applied to study viticultural zoning dynamically has explored in depth what future climate scenarios reserve for Aglianico vineyard cultivation and, in general, for the local viticultural sector of Valle Telesina. From the results obtained, we can conclude that:

1) The potential was confirmed of the hybrid land evaluation approach to studying crop adaptation and crop responses to climate change, as well as the importance of simulation modelling application in viticulture zoning;

2) The methodology applied is able to apply the concept of terroir resilience within a target region, representing a novelty in the applied viticultural zoning procedure.

3) Results demonstrate that CC resilience is a site-specific feature since soils having different physical properties can determine strong difference in resilience under the same climate.

4) The procedure enables to evaluate in advance the quality response for each specific soil type and viticulture landscape. This represents a great opportunity for better CC viticulture planning and management.

5) The applied procedure is a real case of active research support for viticultural zoning planning which is able to identify the best areas for Aglianico quality wine production under climate change;

6) In order to preserve the viticultural sector of Valle Telesina after 2040, important choices will need to be made (e.g. introduction of new grapevine cultivars, application of irrigation regime), which must be supported by local decision makers through specific policy measures.

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Author contributions

A. Bonfante conceived, designed and wrote the manuscript; performed the Land Evaluation at STEP 2 and the preliminary environmental analysis of Aglianico land use requirements in the Taurasi area; performed SWAP model simulations under different climate scenarios and analysed the CWSI results; realised the STEP 3 evaluation and the GIS elaboration; supported the STEP 1 analysis.

E. Monaco, carried out the analysis of climate scenarios and the crop thermal requirements at STEP 1; supported the simulation modelling application and the writing of the manuscript.

G. Langella, supported the climate analysis and simulation modelling application.

P. Mercogliano, E. Buchignani, realised the analysed climate scenarios and supported the climate analysis. P. Manna, supported the land evaluation at STEP 2 and the simulation modelling results evaluation STEP 3. F. Terribile, was leader of the EU LIFE + SOILCONSWEB project and responsible for pedological data applied.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2017.12.035>.

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